Rapid response gravitational wave follow-up with the PIRATE robotic telescope

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Rapid response gravitational wave follow-up with the PIRATE robotic telescope

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Abstract

This poster briefly outlines the research being undertaken at The Open University in the search for electromagnetic (EM) counterparts to gravitational wave candidates detected by the LIGO/Virgo Collaboration (LVC). This includes the setup of the PIRATE facility, which is a robotic telescope located in Tenerife, Spain, and is used as both a research and teaching telescope. Additionally the poster describes the methods used to perform rapid follow-up to gravitational wave alerts from LIGO/Virgo, including a description of the types of EM signals that could be discovered. Lastly there is a short summary of the current observing campaign, corresponding to the second LIGO observing run (O2).

1. Introduction

The existence of gravitational waves has been theorised for over 100 years, but they were not detected conclusively until 2015 (Abbott et al., 2016), owing to their incredibly weak signal. Currently there are two main sources of gravitational waves that can be detected; compact binary mergers and burst events, the latter of which has not yet had a confirmed detection. However there have been 3 confirmed detections of compact binary mergers which have all been between binary black holes (GW150914, GW151226 & GW170104). Due to the radiationless nature of black holes and long coalescence timescales it is not expected that electromagnetic (EM) counterparts will be produced when two black holes merge. However the scenario is different when two neutron stars merge because they are expected to produce observable EM counterparts as shown in Figure 1 - this can range all the way from gamma-rays down to radio (Chu, et al., 2016). There is also predicted to be two types of EM emission, firstly a short gamma-ray burst is expected to be released at the time of merger, which would fade through the EM spectrum. And then in the subsequent hours and days an event known as a kilonova might occur, that is powered by the radioactive decay of the neutron rich material that surrounds the newly merged compact object. It is expected that both these events will be visible in the optical and if the event is close/bright enough then they should be observable to ground based telescopes such as PIRATE.

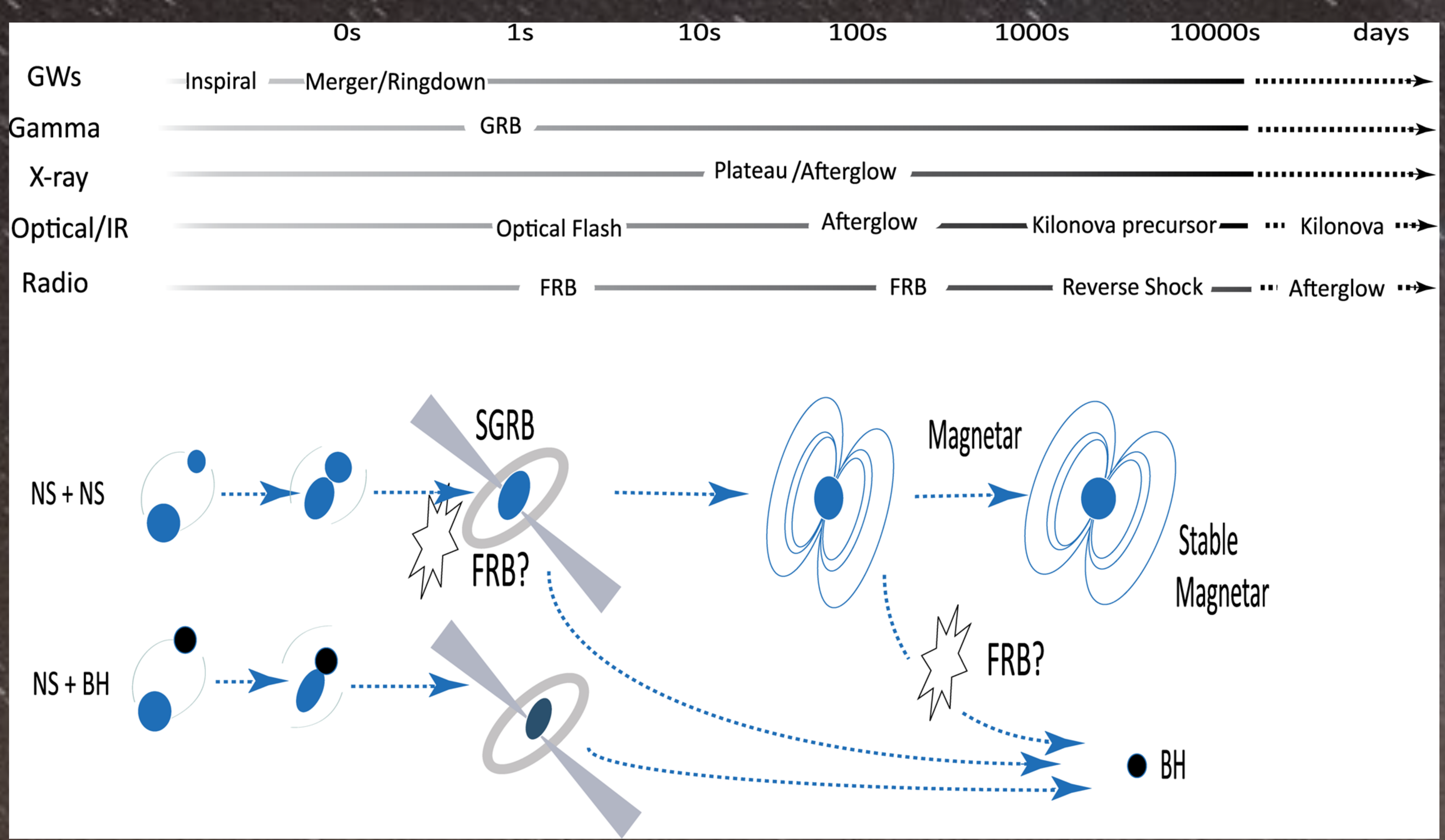


Figure 1. Predicted counterpart time-scales for binary neutron star mergers. (Chu, et al., 2016)

2. PIRATE Facility

Previously PIRATE was located at the Observatorio Astronómico de Mallorca where it made important contributions to time-domain astrophysics research projects, such as monitoring exoplanet transits (Gómez Maqueo Chew, et al., 2013) and eclipsing binaries (Lohr, et al., 2015), but it also played a major role in the teaching of undergraduate astronomy courses at The Open University where it was used to teach undergraduate students the basics of telescope operation. During 2016 the telescope was relocated to the Observatorio del Teide in Tenerife where it is now housed in a new dome atop the 2400m mountain (Figure 2).

PIRATE itself consists of a 17-inch (0.43m) optical tube assembly (OTA) mounted on top of a 10Micron GM4000 HPS mount (Figure 3). Attached to the end of the OTA is a KAF-16803 CCD chip housed within a FLI ProLine PL16803 camera. This camera contains 4096 X 4086 pixels that provide a 43' field of view with a pixel scale of 0.63"/pixel (Kolb, 2014). In addition to this it is equipped with a 7 position filter wheel containing 3 broadband filters (Baader R, G, B), 3 narrowband filters (Hα, OIII, SII) and a clear filter. The telescope is controlled by an automated observatory control software called ABOT that allows students and staff to control the telescope in real time over the internet; as well as schedule observations to be taken during the night. ABOT is also deployed for BlackGEM, Solaris and MeerLICHT (Sybilski, 2015).

Figures 2 & 3. The PIRATE telescope by day in the shadow of Mt Teide and at night under the Milky Way . Image Credits: Johannes Baader

3. Method

One of the key advantages in using a robotic telescope is the rapid response times it can achieve for any astronomical alerts of interest, such as gamma-ray bursts and gravitational waves. However to utilize this it was necessary to create a bespoke pipeline that would process the incoming alerts quickly, but more importantly, without any human intervention. The result was a Python script built on one written by Leo Singer (Singer, 2015) to receive and process gravitational-wave candidate alerts from Advanced LIGO and Virgo via GCN alerts (see Figures 4 & 5).

The alerts contain a sky localization probability map (known as a skymap) and the key step in this process is deciding which areas of the skymap to observe given their relatively large size. Currently this is done using a simple method of highest to lowest probability and with a maximum number of observations cut-off. However an alternative way would be to target individual galaxies within the search area, such as those in the Gravitational Wave Galaxy Catalogue (White, Daw, & Dhillon, 2011), and even potentially in a 3D search volume using the new 3D skymaps (Singer, et al., 2016).

The data is calibrated and plate solved using the image processing software AstroImageJ (Collins K., et al., 2016). We use the source extraction software SExtractor (Bertin E., 2010) to perform photometry on our images, which then gets passed on to a variable star detection software VaST (Sokolovsky & Lebedev, 2017). This generates lightcurves for all the stars in a reference image; from which it then produces a plot of magnitudes against a measure of variability for the lightcurves, typically standard deviation.

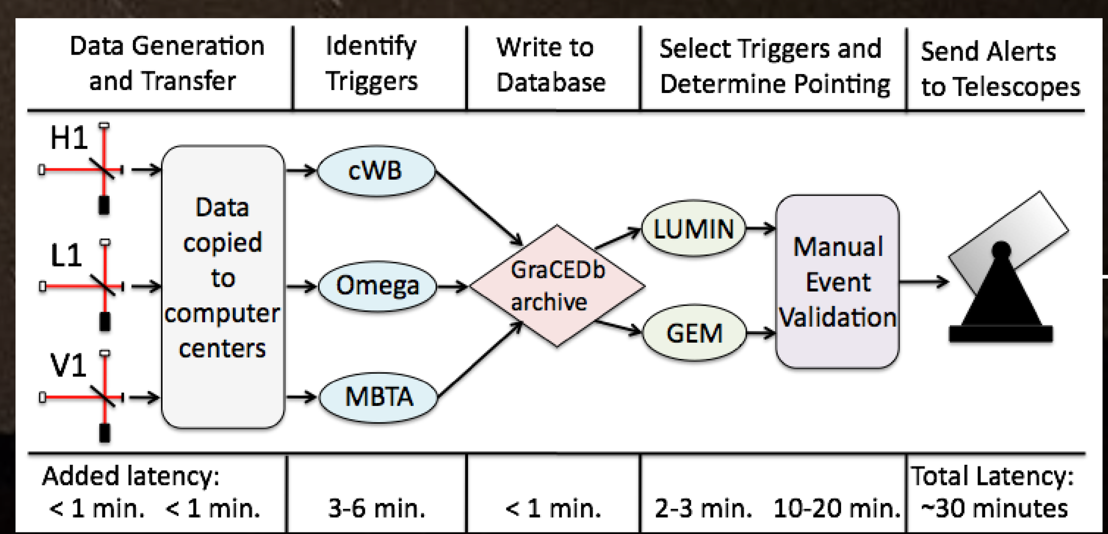


Figure 4. A flowchart showing the different stages of LIGO GW trigger analysis. Image Credit: LIGO/Virgo Collaboration

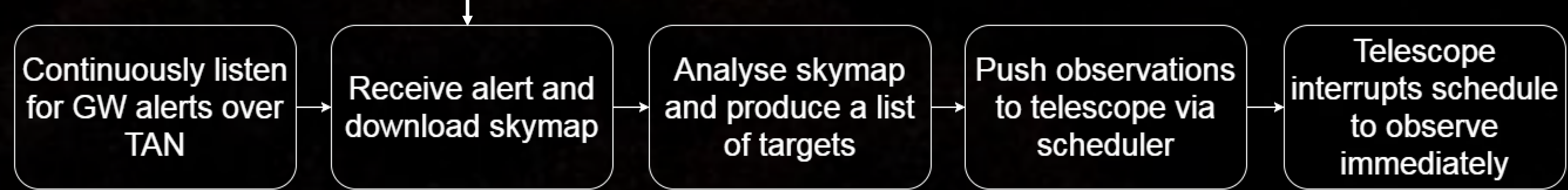


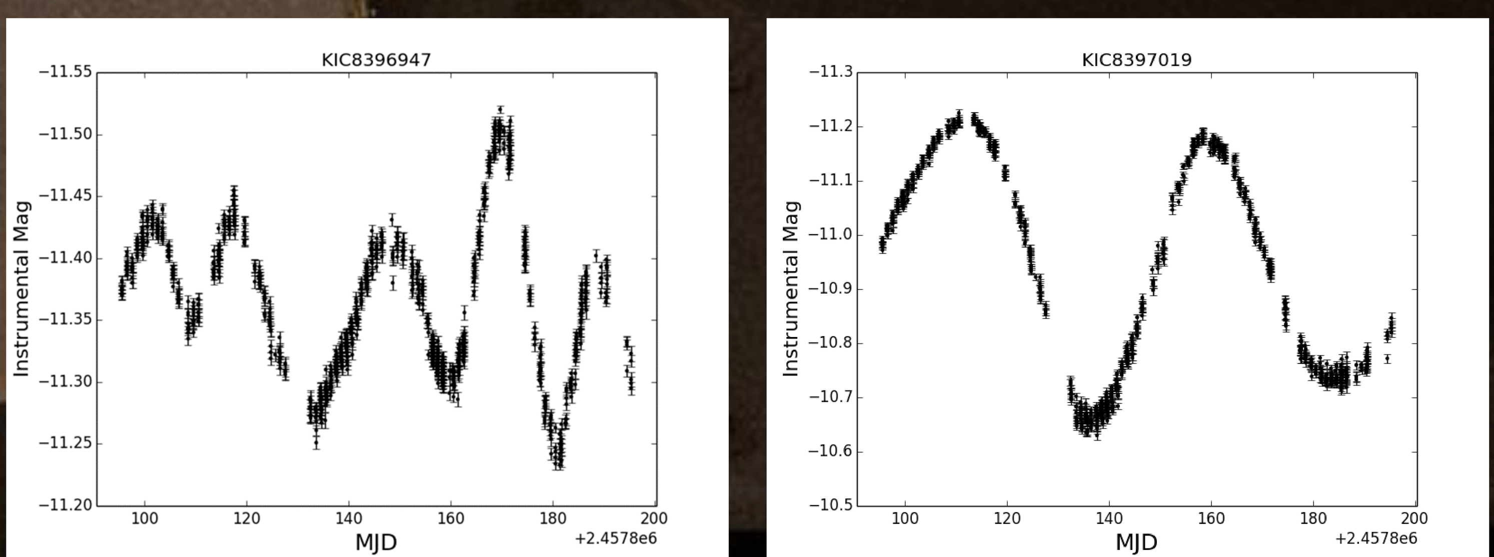
Figure 5. A flowchart showing the different stages of the PIRATE alert pipeline. Image Credit: Simulating Extreme Spacetimes

4. Results

We are currently in the process of analysing all data obtained during the second LIGO observing run (O2) which ran from 30/11/16 to 25/08/17, however due to the embargo surrounding O2 data and results we cannot say any more other than PIRATE performed follow-up observations on 6 of the 8 triggers announced in the June update on the LIGO news website (http://www.ligo.org/news.php).

Up until the 23rd June PIRATE had been observing for 58 nights in total, during which it acquired 1,700 images in search of an EM counterpart corresponding to these 6 gravitational wave candidate alerts, and analysis is ongoing with any results being published in co-operation with the LVC.

The plots in Figures 6 & 7 are taken from a similar research project where PIRATE has been monitoring the Kepler field that contains the variable star KIC8462852 (otherwise known as Tabby's Star) with a high cadence over several months. Both stars shown below are red supergiants that show some irregular pulsating behaviour (Figure 6) over a period of a few days and what appears to be an eclipsing binary (Figure7) with a ~100 day period.



Figures 6 & 7. Lightcurves of two variable stars within the Kepler field, KIC8396947 (left) and KIC8397019 (right), using data taken with the PIRATE telescope.

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Background Image: Edward Hand